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RESEARCH MEMORANDUM

SOME FLYING-QUALITIES STUDIES OF A TANDEM HELICOPTER

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An investigation of the flying qualities of a tandem helicopter is under way to determine the applicability and adequacy of the flying-qualities requirements of the Bureau of Aeronautics Specification NAVAER SR-189 to this type of helicopter and to provide information leading to flying-qualities improvement. The initial results presented herein indicate several basic differences between tandem and previously tested single-rotor helicopters. These results also indicate the tandem test helicopter to have several objectionable flying qualities in forward flight that warrant detailed study of requirement applicability and also study leading to improvement. These results further indicate the longitudinal-divergence requirements of NAVAER SR-189, which are based on the studies of the normal-acceleration characteristics of single-rotor helicopters reported in NACA TN 1983, to be applicable to tandem helicopters, but perhaps to need somewhat more stringency. The presence of an instability with speed, which appears to be a basic problem for the tandem helicopter, is the cause of this uncertainty regarding increased stringency.

The initial results also indicate the most effective means for improving the longitudinal flying qualities to be a reduction in instability with angle of attack. The sources of the instability and the factors that can cause it to vary are discussed and a method is presented which gives promise of reducing this instability with little weight penalty.

Several desirable fields of future investigation are recommended.

INTRODUCTION

During the past few years the National Advisory Committee for Aeronautics has been studying the flying qualities of helicopters in order to set up flying-qualities standards and to determine means for improvement. In reference 1, the outstanding flying-qualities deficiency

encountered in helicopters was reported to be a tendency to diverge in pitch in forward flight. In reference 2, more detailed studies were made on the longitudinal flying qualities of several single-rotor helicopters in forward flight. Based on these studies, reference 2 proposed tentative longitudinal flying-qualities requirements based on the normal-acceleration characteristics during a pull-up maneuver in forward flight. Reference 2 indicates that a helicopter that meets these requirements will be much safer and less fatiguing to the pilot than one which does not. In reference 3, the presence or absence in a helicopter of a divergent tendency in pitch is referred to as the maneuver stability of the helicopter and methods for improving the maneuver stability are discussed. Reference 4, which contains a set of general helicopter flying-qualities requirements, incorporates the tentative requirements of reference 2.

Inasmuch as the requirements of reference 2 are based on studies of single-rotor helicopters, there has been some question as to their applicability and adequacy for tandem helicopters which have grossly different values of many parameters. For example, the moment of inertia in pitch, the damping in pitch, the distance of the pilot forward of the center of gravity, and the longitudinal control power are all likely to be much larger for tandem helicopters than for single-rotor helicopters. It should also be noted that very little background material has been published on the other requirements of reference 4. In particular, although the lateral-directional flying qualities of single-rotor helicopters were felt to be satisfactory enough so as not to need early investigation, familiarization flights by NACA test pilots in tandem helicopters indicated that the lateral-directional flying qualities of tandem helicopters were in need of study. Also, because of the basic differences between tandem and single-rotor helicopters, there is some doubt that the methods proposed in reference 3 to improve the maneuver stability of single-rotor helicopters would be adequate or practical for tandem helicopters. Thus, a study of the flying qualities of tandem helicopters was initiated for two purposes: to determine the applicability and adequacy of the longitudinal and lateral-directional flying-qualities requirements of reference 4 for tandem helicopters and to provide information leading to the improvement of their longitudinal and lateral-directional flying qualities. This paper presents preliminary results of the longitudinal phase of this investigation and, in addition, suggests one means for improving the maneuvering stability of tandem helicopters.

TEST EQUIPMENT

The tandem test helicopter is shown in figure 1. It has a normal gross weight of approximately 7,000 pounds, and the two rotors are of

equal size, each having a diameter of 41 feet. The horizontal and twin vertical stabilizers have areas of approximately 40 and 50 square feet, respectively. The helicopter has conventional pilot controls: stick, rudder pedals, and collective-pitch lever. Longitudinal control is achieved by a longitudinal motion of the stick, which produces a combination of simultaneous longitudinal cyclic pitch and differential collective pitch, the latter providing a large-magnitude pitching moment. Lateral control is achieved by lateral motion of the stick which causes simultaneous lateral cyclic pitch, while directional control is achieved by use of the rudder pedals which causes differential lateral cyclic pitch. Movement of the collective-pitch control changes the collective pitch of both rotors simultaneously. The machine was equipped with standard NACA recording instruments with synchronized time scales that measured pitching velocity, control position, and normal acceleration at the pilots' seats. For the tandem helicopter with the pilot far forward of the center of gravity, the normal acceleration at the pilots' seats may be significantly different from the normal acceleration at the center of gravity, which is the quantity usually measured. For flying-qualities studies, the normal acceleration at the pilots' seats is considered to be more significant.

To aid the pilot in performing the desired pull-up maneuvers, a mechanical device with adjustable stops for limiting the longitudinal stick travel was installed.

QUALITATIVE RESULTS

After their first familiarization flights in the test helicopter, the two project test pilots both reported the ship to have several objectionable flying qualities, both in the longitudinal and the lateral-directional senses. The objectionable flying qualities were primarily caused by a lack of stability and the presence of untrimmed and erratic stick forces and were considered to confirm the need for detailed study of requirement applicability and also study leading to improvement. The directional stability characteristics particularly bothered the pilots because the directional control is relatively weak, being much less powerful than the longitudinal control, hence requiring considerable effort to control the frequent directional deviations.

It was felt that the lack of longitudinal stability is a basic rotor problem and, hence, of more general interest and worthy of earlier study than the directional stability characteristics which are felt to be more of a fuselage-stability and weak-control problem. Thus, the subsequent flights were devoted primarily to taking records of pull-up maneuvers, which are considered by the pilots to be a suitable index of the longitudinal characteristics in normal flight. During normal flight

at all the flight conditions at which pull-ups were measured, the pilots objected to the stick forces and to an instability with speed. However, this preliminary paper deals mainly with stick-fixed longitudinal stability at substantially constant speed.

QUANTITATIVE RESULTS

Pull-up time-history measurements were taken at three different flight conditions, all at an indicated airspeed of about 70 knots, which is approximately the cruising speed of the test helicopter. The three flight conditions will be referred to as conditions A, B, and C, and the measurements are presented in figures 2 to 4, respectively. Flight condition A is level flight with center of gravity near the rearward limit (approximately midway between the rotors). Flight condition B is level flight with center of gravity toward the forward limit. Flight condition C is with center-of-gravity position the same as for flight condition B but with engine power about one-half the value for level flight. The trim rate of descent for condition C was approximately 1,100 feet per minute. Flight condition A was planned to have the worst maneuver stability and hence it was set at a relatively high altitude to insure a thrust coefficient equal to or higher than the thrust coefficient for the other conditions inasmuch as reduced thrust coefficient was expected to be favorable. The thrust coefficient for flight condition A came out to be about 5 percent higher than for the other flight conditions.

Flight Condition A

Normal acceleration.- To clarify this and the subsequent normal-acceleration time histories, faired lines have been drawn from the start of the records to the time when control recovery is initiated. The normal-acceleration time history appears undesirable in nature in showing no tendency to reach a constant or maximum value. As pointed out in reference 2, a divergent tendency in the normal acceleration would be expected to cause adverse pilot impressions. Also to be noted is a slight pause in the development of normal acceleration following the initial rapid rise at the time of control displacement.

Pitching velocity.- The pitching-velocity record shows that maximum angular acceleration is achieved quickly following control displacement but that little or no tendency to reach a constant value of pitching velocity exists. In fact, after the initial concavity downward, there appears to be a slight concave upward tendency starting about $1\frac{1}{2}$ seconds after the start of the maneuver. As pointed out in reference 2, the

attainment of an approximately constant angular velocity is basically what is expected from a fixed control displacement.

Pilot's comments.- The pilot reported the aircraft to have an objectionable divergence in pitch at this condition. The divergence was of less concern to the pilot than the divergence of helicopter A of reference 2, at least partly because of the more powerful control available for recovery in the test helicopter. The divergence in normal acceleration was more noticeable to the pilot than the divergence in pitching velocity.

Flight Condition B

Normal acceleration.- The normal-acceleration curve shows a definite tendency to reach a peak, becoming concave downward at approximately 2 seconds after the start of the maneuver. However, the peak acceleration is not quite reached at the time of recovery, which is more than 4 seconds after the start of the maneuver. The short pause in the development of normal acceleration following the initial rapid rise is again evident. (The normal-acceleration record has less high frequency motion than that of fig. 2 because a different accelerometer of lower natural frequency was used.)

Pitching velocity.- The maximum angular acceleration is again reached quickly following control displacement. The pitching velocity shows a very slow tendency to reach a peak. It again shows the reversal in curvature at about $1\frac{1}{2}$ seconds after the start of the maneuver, but the curve becomes concave downward again at about 3 seconds after the start of the maneuver.

Pilots' comments.- Both test pilots flew the helicopter in this flight condition, and they both considered it to have objectionable divergence in pitch. The pilot who had flown in flight condition A reported the divergence to be less objectionable than for that flight condition.

Flight Condition C

Normal acceleration.- The time history of normal acceleration shows a very strong early tendency to peak, becoming concave downward less than $1\frac{3}{4}$ seconds after the start of the maneuver and reaching a peak at about $2\frac{3}{4}$ seconds after the start of the maneuver. The slight pause in the development of the normal acceleration following the initial rapid rise is again evident.

Pitching velocity.- The maximum angular acceleration is again reached quickly following control displacement. The pitching velocity, like the normal acceleration, shows a strong early tendency to peak although a slight upward curvature exists from about 2 to about $3\frac{1}{2}$ seconds after the start of the maneuver.

Pilots' comments.- The two test pilots also flew the helicopter in this flight condition, and they both considered it to have satisfactory maneuver stability. They were still not fully satisfied with the longitudinal flying qualities, however, because of the undesirable stick forces and the instability with speed.

The slight pause in the development of normal acceleration following the initial rapid rise was not considered objectionable.

DISCUSSION

Comparison Between Pilots' Opinions and Flying-Qualities Requirements of Reference 2

Wording of divergence requirement.- The divergence requirement of reference 2, which is based on studies of single-rotor helicopters, is worded as follows:

> When the longitudinal control stick is suddenly displaced rearward 1 inch from trim (while in level flight at the maximum placard speed) and held fixed at this displacement, the time history of normal acceleration shall become concave downward within 2 seconds following the start of the maneuver.

The requirement is for maximum placard speed because this speed is likely to be most critical. Reference 4 requires the test to be made at several forward speeds. The tests reported herein were made near cruising speed for convenience, but the actual speed chosen is considered to be of secondary importance for comparison of the pilots' opinions with the requirement.

Flight condition A.- The normal-acceleration time history of flight condition A fails to meet the requirements of reference 2 in that it is not even concave downward at the time of recovery, which is $2\frac{1}{2}$ seconds after the start of the maneuver. Thus, the requirement applies in this case in that the test helicopter does not meet the requirement and its longitudinal divergence is objectionable to the pilot.

Flight condition B.- The normal-acceleration time history of flight condition B barely meets the requirements of reference 2 in that it becomes concave downward at about 2 seconds after the start of the maneuver. Thus, the fact that the pilots considered the helicopter to have objectionable longitudinal divergence at this flight condition indicates that the requirement of reference 2 did not apply in this intermediate condition. As is explained subsequently, it is not yet clear that this discrepancy calls for a change in the requirement.

Flight condition C.- The normal-acceleration time history of flight condition C easily meets the divergence requirement of reference 2 in that it is concave downward in less than $1\frac{3}{4}$ seconds after the start of the maneuver. Thus, the requirement applies in this case in that the maneuver stability is satisfactory both according to the requirement and according to the pilots' opinions.

Applicability of divergence requirement to tandem helicopters.- This comparison between the divergence requirement of reference 2 and the pilots' opinions indicates the requirement to be applicable in general to tandem helicopters with their grossly different parameters.

Reasons for pilots' comments on condition B.- Inasmuch as the pilots objected to the characteristics of the pull-up of figure 3 but considered the pull-up of figure 4 to be satisfactory, comparison between the two figures should provide some clue to the characteristics of figure 3 which bothered the pilots. One difference between figures 3 and 4 is the difference in the time for the normal-acceleration time history to become concave downward. However, according to reference 2 a time interval of 2 seconds between the start of the maneuver and the start of the downward concavity as exists in figure 3 is normally satisfactory to the pilots. Thus, some other characteristic is probably responsible.

It is likely that the pilots objected to the normal-acceleration time history of figure 3 even though it becomes concave downward at about 2 seconds because of the long time to reach a peak. Note the much shorter time to peak in figure 4. Reference 2 indicates that for single-rotor helicopters, when the normal acceleration is concave downward by 2 seconds, the peak follows soon after. In figure 5 is presented a pull-up maneuver time history for one of the single-rotor helicopters of reference 2. Note that the peak follows the downward concavity by about 1 second. Apparently, there is some factor which allows the test tandem helicopter in flight condition B to meet the requirement and still take a long time to peak. Possible factors involved are discussed in the section entitled "Factors Affecting Maneuver Stability."

Another possible cause for the pilots' dissatisfaction with the pull-up of figure 3 may be the long time interval for the pitching velocity to approach a peak. In figure 4, the pitching velocity becomes almost flat about $1\frac{1}{2}$ seconds after the start of the maneuver. The reversal in curvature of the pitching-velocity record of figure 4 did not bother the pilots, although it is possible that the reversal in curvature in figure 3 may have accentuated the undesirability of the long time interval to approach a peak. For the single-rotor helicopters studied in reference 2, desirable pitching-velocity characteristics were reached more readily than desirable normal-acceleration characteristics. Note in figure 5 that the pitching velocity becomes concave downward more rapidly than the normal acceleration. Hence, the requirement based on normal acceleration was sufficient to insure fairly satisfactory maneuver stability. Figure 3 indicates that, for tandem helicopters, the presence of normal-acceleration characteristics that meet the divergence requirement does not necessarily insure desirable pitching-velocity characteristics. Possible reasons for this situation are also discussed in the section entitled "Factors Affecting Maneuver Stability."

It is considered that, between the two possible causes for the pilot dissatisfaction, the long time to peak of the normal acceleration of figure 3 is more likely to be the primary factor bothering the pilots, inasmuch as it is known that pilots are more sensitive to normal-acceleration changes than to pitching-velocity changes.

<u>Alternate form of divergence requirement</u>.- Reference 2 presents an alternate form of the divergence requirement, the fulfillment of which is considered to require simpler instrumentation and less judgment. This alternate form is worded as follows:

> When a disturbance is produced by displacing the longitudinal control stick rearward 1/2 inch from trim for 1/2 second and then returning to trim and holding the trim setting, the following qualities shall be demonstrated: (1) The value of normal acceleration g shall not increase by more than 1/4g $\left(\text{total, } 1\frac{1}{4}\text{g}\right)$ within 10 seconds from the start of the disturbance; and (2) during the subsequent nose-down motion (with controls still fixed at trim), the value of acceleration shall not fall below 3/4g within 10 seconds, the 10 seconds being measured from the time of initial return to 1 g.

Several attempts were made to check the applicability of this form of the divergence requirement to the test tandem helicopter. However, in almost every case, because of a large nose-up attitude, the pilot felt it necessary to apply recovery control before the stated time

intervals were reached and without a change in "g" in excess of the stated requirements. Examination of the problem indicated that the large nose-up attitude was apparently caused by the instability with speed and the associated speed reduction. Thus, it appears necessary to remove the instability with speed before the applicability of this form of the divergence requirement can be checked.

"Anticipation" requirement.- An additional longitudinal flying-qualities requirement is proposed in reference 2 aimed at reducing the difficulty of anticipating the results of a control deflection. This requirement is worded as follows:

> When the longitudinal control stick is suddenly displaced rearward 1 inch from trim (while in level flight at the maximum placard speed) and held fixed at this displacement, the time history of normal acceleration should preferably be concave downward throughout the period between the start of the maneuver and the attainment of maximum acceleration, and, in any event, the slope of the normal-acceleration curve must remain positive from the start of the maneuver until the maximum acceleration is approached.

In flight condition C, which was satisfactory to the pilots from a divergence standpoint, a short pause in the development of normal acceleration of 0.1 to 0.2 second after the initial rapid rise is evident. As mentioned previously, the pilots did not object to this short development pause, which agrees with the indication in reference 3 that the pause does not have to be completely eliminated to make it acceptable, rather than minimized to 0.1 to 0.2 second length. It is significant that, at least for the condition tested, there is no pause problem for the tandem helicopter even though such a problem might be expected because of the large distance of the pilots forward of the center of gravity.

Factors Affecting Maneuver Stability

Significant stability derivatives.- Reference 3 indicates that the two stability derivatives that have the greatest effect on the pull-up characteristics and hence on the maneuver stability of a helicopter are angle-of-attack stability and damping in pitch. An increase of either of these quantities improves the maneuver stability. Although variations in stability with speed were not previously considered to affect maneuver stability, it would seem desirable to reexamine this possibility for the test helicopter which is noticeably unstable in this regard. Inasmuch as significant speed changes do not occur until several seconds after the start of a pull-up maneuver, only the latter parts of the pull-ups of figures 2 to 4 could be affected by the instability with speed of the test helicopter.

The tandem helicopter has a large amount of damping in pitch, in addition to the damping of the individual rotors, produced by the fore-and-aft disposition of the two rotors. A nose-up pitching velocity, for example, reduces the angle of attack and thrust of the front rotor and increases these values for the rear rotor, thus producing a nose-down pitching moment. Calculations indicate that, for the test helicopter in cruising flight, the damping produced by the fore-and-aft disposition of the two rotors is of the order of twenty times the damping produced by the individual rotors. It is therefore concluded that the objectionable longitudinal divergence in flight condition A reported by the pilot is caused primarily by an instability with angle of attack, and possibly in addition, in the later stages of the maneuver, by an instability with speed. In flight condition B, an instability with speed may have produced nose-up moments during the latter part of figure 3, causing the long time to peak in spite of the downward concavity in normal acceleration at about 2 seconds, and hence, may be responsible for the inapplicability of the requirement. If so, inasmuch as positive speed stability is now generally required in its own right (see references 4 and 5), no change in the maneuver requirement would actually be necessary.

<u>Sources of angle-of-attack instability</u>.- The rotors and the fuselage can both contribute to angle-of-attack instability. The unstable moment contributed by the rotors is thought to be due to three sources. Firstly, the individual rotors are each unstable with angle of attack just as is the rotor of a single-rotor machine, as indicated in reference 1. Secondly, measurements indicate that the rear rotor is set at a higher collective-pitch angle than the front rotor during steady flight, apparently because it is in the downwash of the front rotor. Even during the pull-up maneuver part of this difference in collective pitch still exists. Thus, the rear rotor can be thought of as being in more of a climb condition than the front rotor. As indicated in reference 6, an increase in rate of climb increases the tendency of a rotor to encounter retreating-blade tip stalling. Calculations indicate the test helicopter, like most helicopters, to be close to retreating-blade stalling during cruising flight. Thus, during the pull-up maneuver, there may be a tendency for the rear rotor to stall first and hence add to the angle-of-attack instability by a reduction in its lift slope. Thirdly, the operation of the rear rotor in the downwash field of the front rotor produces another source of instability, similar to the loss in effectiveness of the horizontal stabilizer of an airplane when operating in the wing-downwash field. When the helicopter angle of attack is increased, the rear-rotor angle of attack, and hence the rear-rotor thrust, increases less than the angle of attack and thrust of the front rotor, because of the increased downwash angle from the front rotor.

1. individual rotors unstable with α
2. rear rotor at greater climb (due to downwash) than front rotor — more susceptible to ret. tip stalling, which ~~[illegible]~~ reduces lift curve slope
3. Because of front rotor downwash, rear rotor α & thrust increases less than front rotor α & T, making for greater instability

Wind-tunnel tests presented in reference 7 of a model of the test helicopter without rotors indicate the fuselage with stabilizers attached to be approximately neutrally stable with angle of attack. The horizontal stabilizer may be less effective in flight than indicated in the wind-tunnel tests because it is operating in the downwash of the rotors, thus causing the fuselage-stabilizer combination to contribute some angle-of-attack instability. However, calculations indicate that this loss in stabilizer effectiveness is only about 15 percent and is not large enough to be the major cause of the angle-of-attack instability. Thus, it is concluded that the rotor system is the major source of the angle-of-attack instability.

Causes of variations in angle-of-attack stability among the three flight conditions.- It seems probable that the forward movement of the center of gravity and the reduction in thrust coefficient in going from flight condition A to flight condition B shortened the time to downward concavity in the normal-acceleration time history by causing a reduction in angle-of-attack instability. A forward shift in the center of gravity is thought to reduce the angle-of-attack instability in two ways. Firstly, forward movement is desirable, just as in the fixed-wing airplane, to get the center of gravity forward of the aerodynamic center of the machine. Secondly, forward movement of the center of gravity unloads the rear rotor and hence reduces rear-rotor stalling, thus preventing reduction in its lift slope. The reduction in thrust coefficient in going from figure 3 to figure 4 is probably also helpful because it reduces rear-rotor stalling.

The improvement in maneuver stability in going from flight condition B to the reduced-power flight condition C is also attributed to a large improvement in angle-of-attack stability. A reduction in power with the resulting rate of descent is thought to improve the angle-of-attack instability in three ways. Firstly, as indicated in reference 8, a reduction in power reduces the angle-of-attack instability of the individual rotors. Secondly, as mentioned previously, reference 6 indicates an increasing rate of descent to reduce the tendency of a rotor toward retreating-blade tip stalling. Thus, the instability contribution caused by rear-rotor stalling is reduced by reducing power. The third source of improvement in angle-of-attack stability with reduced power is thought to be a nonuniformity of flow angle through the front-rotor downwash field. Vertical traverse measurements of downwash angle behind a rotor presented in reference 9 indicate, in general, a maximum value of downwash angle in approximately the middle of the rotor wake. Thus, during steady level flight, when the rear rotor and horizontal stabilizer are above the center of the front-rotor wake, they will approach the center of the wake during the pull-up maneuver. The angle of attack and lift decrease, and hence the nose-down moment contributed by the rear rotor and horizontal stabilizer, will therefore be reduced below the values that would occur if the front-rotor downwash were uniform. Similarly, during a pull-up from a

partial-power descent condition, the rear rotor and horizontal stabilizer move out of the front-rotor wake, thus experiencing less of a downwash increase than normal.

The nonuniformity of the front-rotor downwash angle may also be the cause of a nonlinearity in the angle-of-attack stability. Any change in the variation of downwash angle with vertical distance would result in a change in slope of moment against angle of attack. As indicated in the vertical-downwash traverses of reference 9, such changes in downwash-angle variation with vertical distance do exist. Such a nonlinearity could also be caused by rear-rotor stalling. The importance of such a nonlinearity is now discussed.

Effects of Downwash and Stalling on Factors Appreciated by the Pilots

It was previously stated that the pilots' dissatisfaction with the characteristics of the helicopter in flight condition B was probably due to one of two causes: either the long time to peak of the normal acceleration and pitching velocity of flight condition B in spite of the downward concavity in normal acceleration at about 2 seconds after the start of the maneuver, or normal-acceleration characteristics that meet the divergence requirement not insuring desirable pitching-velocity characteristics. The instability with speed was given as one possible cause for the long time to peak. A nonlinearity in angle-of-attack stability such that the instability increased with increasing angle of attack, as could be caused by either downwash or stalling effects, could have a similar consequence. These stalling and downwash effects may also be preventing desirable normal-acceleration characteristics from insuring desirable pitching-velocity characteristics in that, if the rear-rotor thrust does not build up in a linear manner during the pull-up maneuver, the result would be a tendency for the normal acceleration to become concave downward because of the reduction in lift slope but for the pitching velocity to continue to increase.

METHOD TO REDUCE ANGLE-OF-ATTACK INSTABILITY

In order to improve the maneuver stability of the tandem helicopter in level flight, on the basis of the previous discussion of test results, first consideration should be given to reducing the angle-of-attack instability. An increase in the size of the horizontal tail surface is one possibility, but such an increase involves a weight penalty. In reference 10, successful stabilization of a helicopter somewhat similar to the test machine by use of an automatic pilot is

reported. However, assuming that an autopilot is used, it seems to be generally agreed by the regulatory agencies that the inherent stability of the helicopter should be satisfactory in consideration of autopilot failure possibilities. One method for reducing the inherent angle-of-attack instability of the tandem helicopter which appears to involve little weight penalty has been devised and subjected to theoretical analysis. This method consists of reducing the slope of the lift curve of the front rotor with respect to the rear rotor by means of a δ_3 angle in the flapping hinges of the front rotor. (See appendix A for definition of δ_3 angle.) Such a linkage reduces blade pitch when the flapping angle is increased. With positive δ_3 on the front rotor, and zero or some small negative δ_3 on the rear rotor, a large increment in angle-of-attack stability can be produced. This increment in stability comes about as follows: When the helicopter angle of attack is increased, the thrust on both rotors is increased, causing an increase in rotor-blade coning angle. Because of the differential δ_3, the collective pitch on the front rotor will be reduced below its trim value while the collective pitch on the rear rotor will remain the same, or be increased somewhat. The result is a nose-down, and hence stabilizing, pitching moment. In appendix B sample calculations on the amount of angle-of-attack stability that can be produced by this differential δ_3 are presented. These sample calculations indicate that, for the test helicopter, the equivalent of approximately 80 square feet of tail surface area can be obtained. There is also some discussion in appendix B of other effects caused by this differential δ_3 configuration which should be considered in its development.

IRREVERSIBLE CONTROL SYSTEMS

The undesirable stick forces objected to by the pilots are apparently due to forces fed in by the rotors and to an interaction of the controls. Reference 1 recommends the use of substantially irreversible control systems to prevent rotor forces from reaching the controls, with the desired feel forces introduced at the pilot's side of the irreversible mechanism. Such irreversible control systems could also prevent the objectionable control interaction.

Irreversible control systems could also have another desirable effect. Control-position pickups located at the rotor hubs of the test helicopter indicate the possibility of cable stretch during the pull-up maneuver, resulting in movement of the rotor swash plates such as to cause nose-up pitching moments on the helicopter. If the irreversible unit is located near the rotor hub, it would prevent rotor forces from reaching and stretching the control cables.

FUTURE RESEARCH

The preliminary results presented herein indicate the desirability of several future fields of investigation. A more thorough check of the applicability of the maneuver-stability requirements of reference 2 appears desirable. This check could conveniently be made by varying the maneuver stability by varying the rate of descent. As part of this check, the cause for the possible need for increased stringency of the requirement should be investigated. As mentioned previously, perhaps removal of the instability with speed is all that is necessary to make the requirement adequate. Inasmuch as the requirement of reference 2 is based on studies of helicopters with positive speed stability, and inasmuch as positive speed stability is now generally required, it would appear desirable to eliminate the instability of the test helicopter with speed before proceeding with the more thorough check of these requirements. If elimination of the instability with speed fails to make the requirement adequate, it may be necessary to add a requirement, perhaps on the time to maximum acceleration or on some characteristics of the pitching velocity.

Another desirable field of investigation appears to be a more thorough study of the causes of angle-of-attack instability of tandem helicopters, such as the stalling and downwash effects. This study should determine which combination of flight conditions is most critical and might also provide clues for other means to remove the angle-of-attack instability. For example, the apparently favorable effects of forward center-of-gravity movement appear to warrant further investigation. Such a study of the causes of angle-of-attack instability might also provide a means for developing a theoretical method for predicting the angle-of-attack stability of tandem helicopters.

The instability with speed of the test helicopter appears to be a basic problem for the tandem configuration. Flow-angle changes at the rear rotor due to changes in the front-rotor downwash with forward speed are suspected as being a major source of this instability. The downwash studies suggested in the previous paragraph might also provide significant information on this subject.

The lateral-directional flying qualities of tandem helicopters also appear to warrant more thorough study. Such an investigation should aim at determining the adequacy of the lateral-directional flying-qualities requirements of reference 4 and providing information leading to improvement.

CONCLUDING REMARKS

An investigation of the flying qualities of a tandem helicopter has been undertaken. Initial results indicate the test helicopter to have several objectionable flying qualities in forward flight that warrant study leading to improvement. The results also indicate the maneuver-stability requirement of NACA TN 1983, which is based on studies of single-rotor helicopters, to be applicable to tandem helicopters, but perhaps to need some modification, inasmuch as for one intermediate condition, the pilots objected to a divergent tendency in pitch even though the requirement was met. This possible need for greater stringency may be due to an instability with speed, perhaps to a nonlinearity in angle-of-attack stability, or perhaps, unlike the situation for the single-rotor helicopters tested previously, to the failure of satisfactory normal-acceleration characteristics to insure satisfactory pitching-velocity characteristics. If instability with speed is the cause, no increase in stringency is actually necessary inasmuch as positive speed stability is now generally required in its own right.

The initial results also indicate the primary flying-qualities difficulty, longitudinally, to be an instability with angle of attack caused by the rotors. The instability is reduced by a combination of forward center-of-gravity movement and reduction in thrust coefficient and even more by a reduction in power (increased rate of descent), causing a corresponding improvement in longitudinal flying qualities.

A method is presented to add stability with angle of attack in order to help make the longitudinal flying qualities satisfactory at all flight conditions. The method, which appears to involve little weight penalty, consists of reducing the lift-curve slope of the front rotor with respect to the rear rotor by use of a δ_3 angle in the flapping hinges of the front rotor.

The initial results indicate the desirability of several future investigations. A more thorough check of the applicability of the maneuver-stability requirement of NACA TN 1983 appears desirable, after first eliminating the instability with speed of the test helicopter. A more thorough investigation of the causes of angle-of-attack instability and instability with speed of tandem helicopters and a more thorough study of their lateral-directional flying qualities also appear desirable.

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APPENDIX A

SYMBOLS

Physical Quantities

b	number of blades per rotor
r	radial distance to blade element, feet
R	blade radius, feet
c	blade-section chord, feet
c_e	equivalent blade chord (on thrust basis), feet $\left(\dfrac{\int_0^R cr^2dr}{\int_0^R r^2dr}\right)$
σ	rotor solidity $(bc_e/\pi R)$
θ	blade-section pitch angle; angle between line of zero lift of blade section and plane perpendicular to axis of no feathering, radians
I_1	mass moment of inertia of blade about flapping hinge, slug-feet^2
ρ	mass density of air, slugs per cubic foot
γ	mass constant of rotor blade, expresses ratio of air forces to mass forces $\left(c\rho aR^4/I_1\right)$
δ_3	angle in plane of rotation between perpendicular to blade-span axis and flapping-hinge axis, positive when an increase in flapping produces a decrease in blade pitch
A_t	area of horizontal stabilizer
d	distance between rotors

Air-Flow Parameters

V	true airspeed of helicopter along flight path, feet per second
Ω	rotor angular velocity, radians per second
α	rotor angle of attack; angle between relative wind and plane perpendicular to axis of no feathering, positive when axis is pointing rearward, radians
α_t	stabilizer angle of attack
μ	tip-speed ratio $\left(\frac{V \cos \alpha}{\Omega R}\right.$ assumed equal to $\left.\frac{V}{\Omega R}\right)$

Aerodynamic Characteristics

a	slope of curve of section lift coefficient against section angle of attack, per radian
L_t	stabilizer lift, pounds
C_{L_t}	stabilizer lift coefficient $\left(\frac{L_t}{\frac{1}{2}\rho V^2 A_t}\right)$
T	rotor thrust, component of rotor resultant force parallel to axis of no feathering, pounds
C_T	rotor thrust coefficient $\left(\frac{T}{\pi R^2 \rho (\Omega R)^2}\right)$

Rotor-Blade Motion

β	blade flapping angle at particular azimuth position, radians
a_o	constant term in Fourier series that expresses β; therefore, rotor coning angle

Miscellaneous

Δ increment

$t_{a,b}$ functions of μ given in reference 10; subscripts a and b represent numbers used to identify a particular function

Subscripts

f front rotor

r rear rotor

APPENDIX B

ANALYSIS OF TANDEM HELICOPTER ANGLE-OF-ATTACK STABILIZATION BY DIFFERENTIAL δ_3

In order to obtain the order of magnitude of the change in angle-of-attack stability provided by different amounts of δ_3 angle on the front and rear rotors, the following simplifying assumptions are made:

(1) Fuselage and horizontal stabilizer combined pitching moments are equal to zero.

(2) Flapping hinges are on the rotor shaft.

(3) The trim values of thrust on the two rotors are equal; thus, the center of gravity lies on the midpoint between the trim positions of the two thrust vectors.

(4) The downwash angle at the rear rotor due to the lift of the front rotor is given by $\frac{C_{T_f}}{2\mu^2}$, where C_{T_f} is the thrust coefficient of the front rotor. This same downwash angle is used for a horizontal tail surface placed below the rear rotor to provide angle-of-attack stability. (This assumption implies that the tail surface is not affected by downwash from the rear rotor.)

(5) The rear rotor produces no upwash at the front rotor.

(6) Changes in the individual rotor angle-of-attack instabilities due to the δ_3 hinges are small enough to be neglected.

(7) Changes in coning angle due to normal-acceleration changes on the blades are small enough to be neglected.

Consider a tandem helicopter in forward flight subjected to an increase in angle of attack. Because of the change in inflow through the rotors, there is an increase in thrust and, hence, an increase in coning angle on both rotors. By using a δ_3 angle on the front-rotor flapping hinges, this increased coning angle can be used to reduce collective pitch of the front rotor sufficiently to reduce its thrust increase below that of the rear rotor, thus producing a stable, nose-down moment. Some additional stable pitching moments could be obtained by putting some negative δ_3 on the rear rotor.

If the two rotors are the same size, have the same solidity, and are run at the same tip speed, their lift slopes are proportional to the derivative $\frac{\partial\left(C_T/\sigma\right)}{\partial\alpha}$. The change in $\frac{\partial\left(C_T/\sigma\right)}{\partial\alpha}$ due to a δ_3 hinge can be computed as follows:

$$\Delta\frac{\partial\left(C_T/\sigma\right)}{\partial\alpha} = \frac{\partial\left(C_T/\sigma\right)}{\partial\theta}\frac{d\theta}{d\alpha}$$

$$= \frac{\partial\left(C_T/\sigma\right)}{\partial\theta}\frac{d\theta}{da_o}\frac{da_o}{d\alpha}$$

$$= \frac{\partial\left(C_T/\sigma\right)}{\partial\theta}\frac{d\theta}{da_o}\left(\frac{\partial a_o}{\partial\alpha} + \frac{\partial a_o}{\partial\theta}\frac{d\theta}{d\alpha}\right) \tag{1}$$

where $\frac{d\theta}{da_o} = -\tan\delta_3$ and the second term in the bracket takes account of the fact that a reduction in θ reduces the increase in a_o. Combining equations (1) and (8) of reference 11 (omitting the blade twist and rotor weight terms) gives

$$\frac{a_o}{\gamma} = t_{1,1}\left(\mu\alpha - \frac{C_T/\sigma}{2\mu/\sigma}\right) + t_{1,2}\theta \tag{2}$$

where the symbols $t_{1,1}$ and $t_{1,2}$ represent tabulated constants in reference 11. Differentiating equation (2) gives

$$\frac{\partial a_o}{\partial\alpha} = \gamma t_{1,1}\left[\mu - \frac{\frac{\partial\left(C_T/\sigma\right)}{\partial\alpha}}{2\mu/\sigma}\right] \tag{3}$$

and

$$\frac{\partial a_o}{\partial\theta} = \gamma\left[-\frac{t_{1,1}\frac{\partial\left(C_T/\sigma\right)}{\partial\theta}}{2\mu/\sigma} + t_{1,2}\right] \tag{4}$$

From equation (1) $\frac{d\theta}{d\alpha}$ can be found as follows:

$$\frac{d\theta}{d\alpha} = \frac{d\theta}{da_o}\left(\frac{\partial a_o}{\partial \alpha} + \frac{\partial a_o}{\partial \theta}\frac{d\theta}{d\alpha}\right)$$

$$= -\tan\delta_3\left(\frac{\partial a_o}{\partial \alpha} + \frac{\partial a_o}{\partial \theta}\frac{d\theta}{d\alpha}\right) \tag{5}$$

Therefore

$$\frac{d\theta}{d\alpha} = \frac{-\tan\delta_3\frac{\partial a_o}{\partial \alpha}}{1 + \tan\delta_3\frac{\partial a_o}{\partial \theta}} \tag{6}$$

Combining equations (1), (3), (4), and (6)

$$\Delta\frac{\partial(C_T/\sigma)}{\partial \alpha} = \frac{-t_{1,1}\gamma\tan\delta_3\frac{\partial(C_T/\sigma)}{\partial \theta}\left[\mu - \frac{\frac{\partial(C_T/\sigma)}{\partial \alpha}}{\frac{2\mu}{\sigma}}\right]}{1 - \gamma\tan\delta_3\left[\frac{t_{1,1}\frac{\partial(C_T/\sigma)}{\partial \theta}}{2\mu/\sigma} - t_{1,2}\right]} \tag{7}$$

The equivalent additional horizontal-tail-surface area required to produce the same change in angle-of-attack stability as this amount of δ_3 on the front rotor can be computed by equating the moments produced per radian change in angle of attack as follows:

$$A_t\frac{d}{2}\left(\frac{dC_L}{d\alpha}\right)_t\left\{1 - \frac{\left[\frac{\partial(C_T/\sigma)}{\partial \alpha}\right]_f}{2\mu^2/\sigma}\right\}\frac{1}{2}\rho V^2 = \Delta\frac{\partial(C_T/\sigma)}{\partial \alpha}\sigma\rho\pi R^2(\Omega R)^2\frac{d}{2}\left\{1 + \frac{\left[\frac{\partial(C_T/\sigma)}{\partial \alpha}\right]_r}{\frac{2\mu^2}{\sigma}}\right\}$$

The second term in the first brace takes account of the downwash change at the tail surface. The second term in the second brace takes account of the reduction in downwash change at the rear rotor when the lift slope of the front rotor is reduced. Therefore

$$\frac{A_t}{2\pi R^2} = \frac{\Delta \frac{\partial\left(C_T/\sigma\right)}{\partial\alpha} \sigma \left\{1 + \frac{\left[\frac{\partial\left(C_T/\sigma\right)}{\partial\alpha}\right]_r}{2\mu^2/\sigma}\right\}}{\left(\frac{dC_L}{d\alpha}\right)_t \left\{1 - \frac{\left[\frac{\partial\left(C_T/\sigma\right)}{\partial\alpha}\right]_f}{2\mu^2/\sigma}\right\} \mu^2} \tag{8}$$

Examination of equations (7) and (8) reveals, as would be expected, that the more δ_3 used in the front rotor, the greater the increase in angle-of-attack stability attained. However, there are practical limitations to the amount of δ_3 that can be used. Excessive δ_3 may result in "mushiness" and excessive rotor-speed variations during pull-ups or turns. As shown in section 13 of reference 12, excessive δ_3 may also result in insufficient damping in roll in hovering.

A reasonable value of δ_3 to use may be deduced from the following consideration. A particular single-rotor machine currently in use has a δ_3 angle of 23° in autorotation and is considered by the pilots to be satisfactory (tan 23° = 0.42). It seems logical therefore that, inasmuch as $\frac{d\theta}{da_o}$ depends upon the tangent of the δ_3 angle, a tandem-rotor machine could tolerate a δ_3 angle of at least 40° (tan 40° = 0.84) on one rotor without encountering excessive mushiness or rotor-speed variation during pull-ups or turns in autorotation. Assuming a typical blade drag angle of 5° results in a typical value of δ_3 of 35° (tan 35° = 0.7), inasmuch as the normal hub configuration is such as to cause the blade drag angle to reduce the amount of δ_3. Calculations indicate that this value of δ_3 would not cause any appreciable increase in control sensitivity in roll in hovering. This value of δ_3 in the front rotor will be used in the sample calculations that follow. It should be pointed out here that some small amount of negative δ_3, about 5°, is probably tolerable on the rear rotor without reducing flapping stability appreciably. In turn, an additional 5° of δ_3 may then be tolerable on the front rotor from mushiness and rotor-speed-variation considerations.

For the test helicopter, $\sigma = 0.052$ and $\gamma = 10.4$. Thus, assuming $\delta_3 = 35^{\circ}$ on the front rotor, $\left(\frac{dC_L}{d\alpha}\right)_t = 3.5$, and $\mu = 0.30$, using the tabulated values of reference 11 and the charts of reference 8, equations (7) and (8) give

$$\frac{\partial\left(C_T/\sigma\right)}{\partial\alpha} = -0.147$$

and

$$\frac{A_t}{2\pi R^2} = 0.0304$$

For the test helicopter, $2\pi R^2 = 2639$. Thus

$$A_t = 0.0304 \times 2639 = 80.2 \text{ square feet}$$

Thus, for the test helicopter at $\mu = 0.30$, a δ_3 angle of 35° in the front rotor provides approximately as much angle-of-attack stability as 80 square feet of tail-surface area. Additional calculations indicate that at lower speeds, the tail-surface equivalent is even more than 80 square feet.

Two other aspects involved in the use of the differential δ_3 configuration are as follows: Inasmuch as a δ_3 hinge also causes cyclic feathering due to cyclic flapping, it is probably necessary to rotate somewhat in the direction of rotation the positions of maximum longitudinal and lateral cyclic pitch of the front rotor. The single-rotor helicopter previously referred to as having a δ_3 angle of 23° in autorotation has a rotation of the maximum cyclic-pitch position that averages approximately one-half the δ_3 angle for all power conditions, which apparently is satisfactory. From examination of the problem, the exact amount of rotation does not appear to be critical so that a cut-and-try method using this value of one-half for a first guess appears to be a practical approach to the determination of the proper value.

It will probably also be necessary to increase and shift upward the collective-pitch range of the front rotor. Calculations indicate approximately a 25-percent increase in range and a 2° upward shift of the lower end of the range to be desirable for a δ_3 angle of 35°. A cut-and-try method starting with these values appears to be a practical approach to determine the optimum values of range increase and upward shift also.

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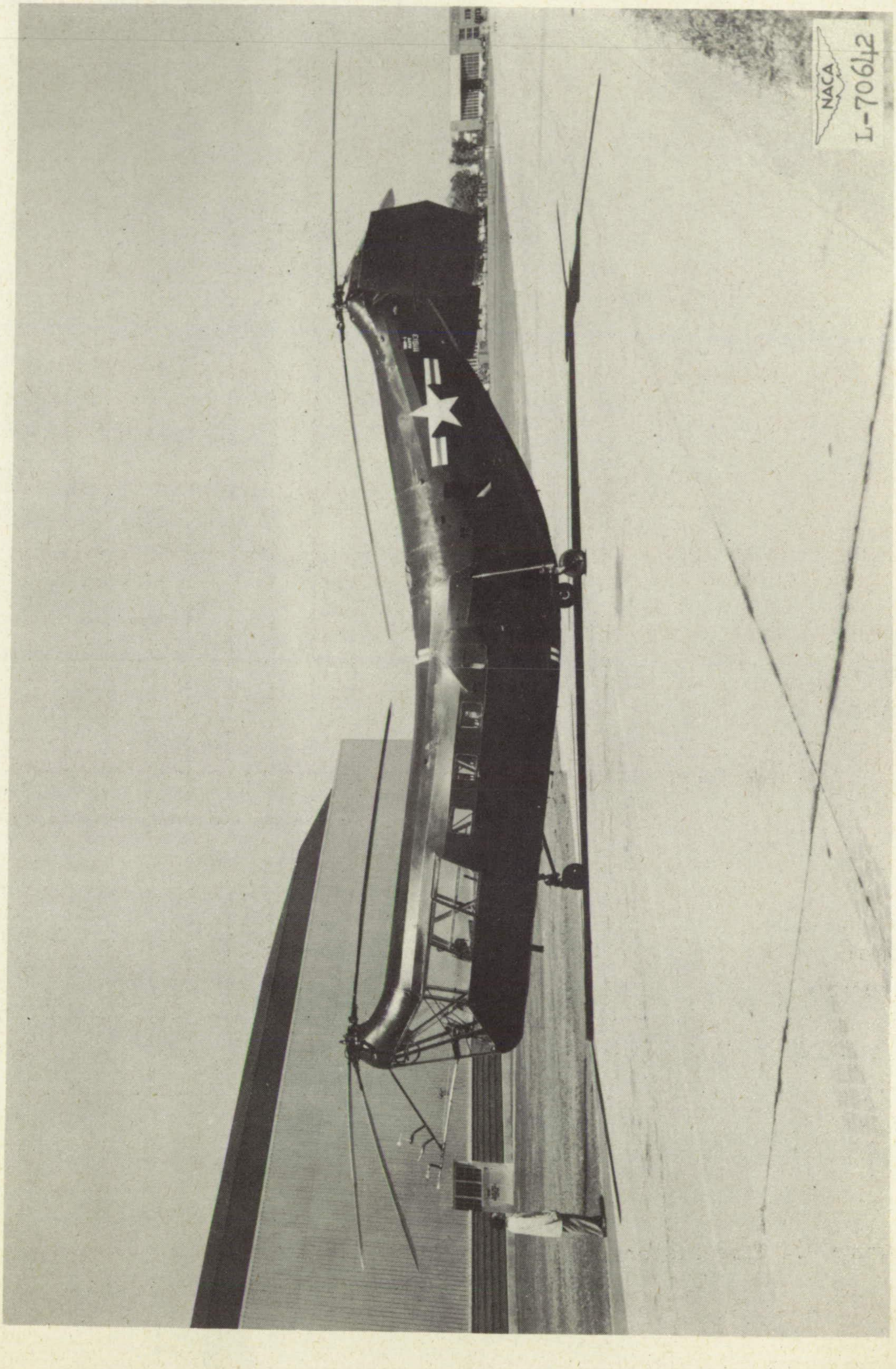

Figure 1.- Test helicopter.

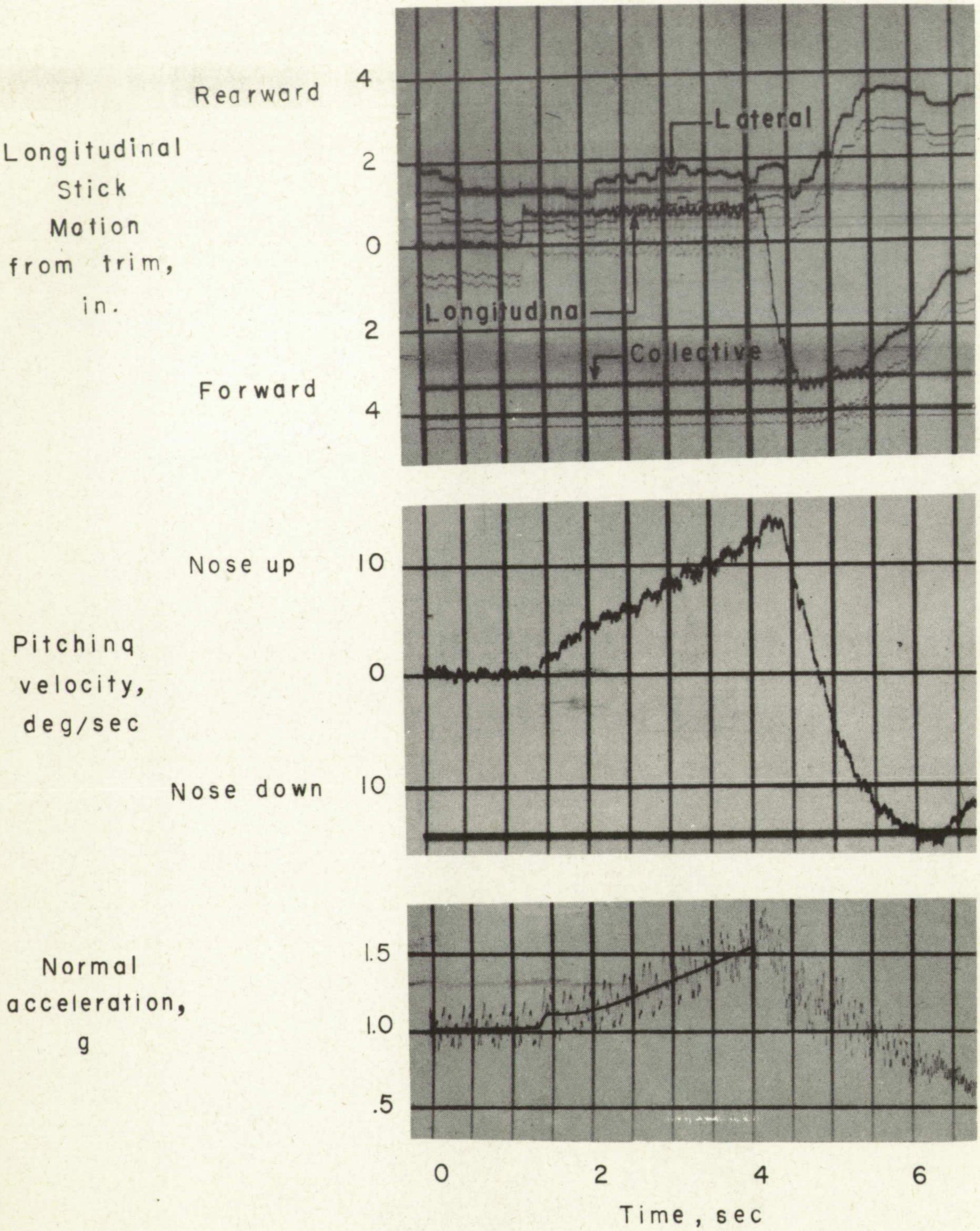

Figure 2.- Time history of pull-up maneuver for tandem helicopter at flight condition A.

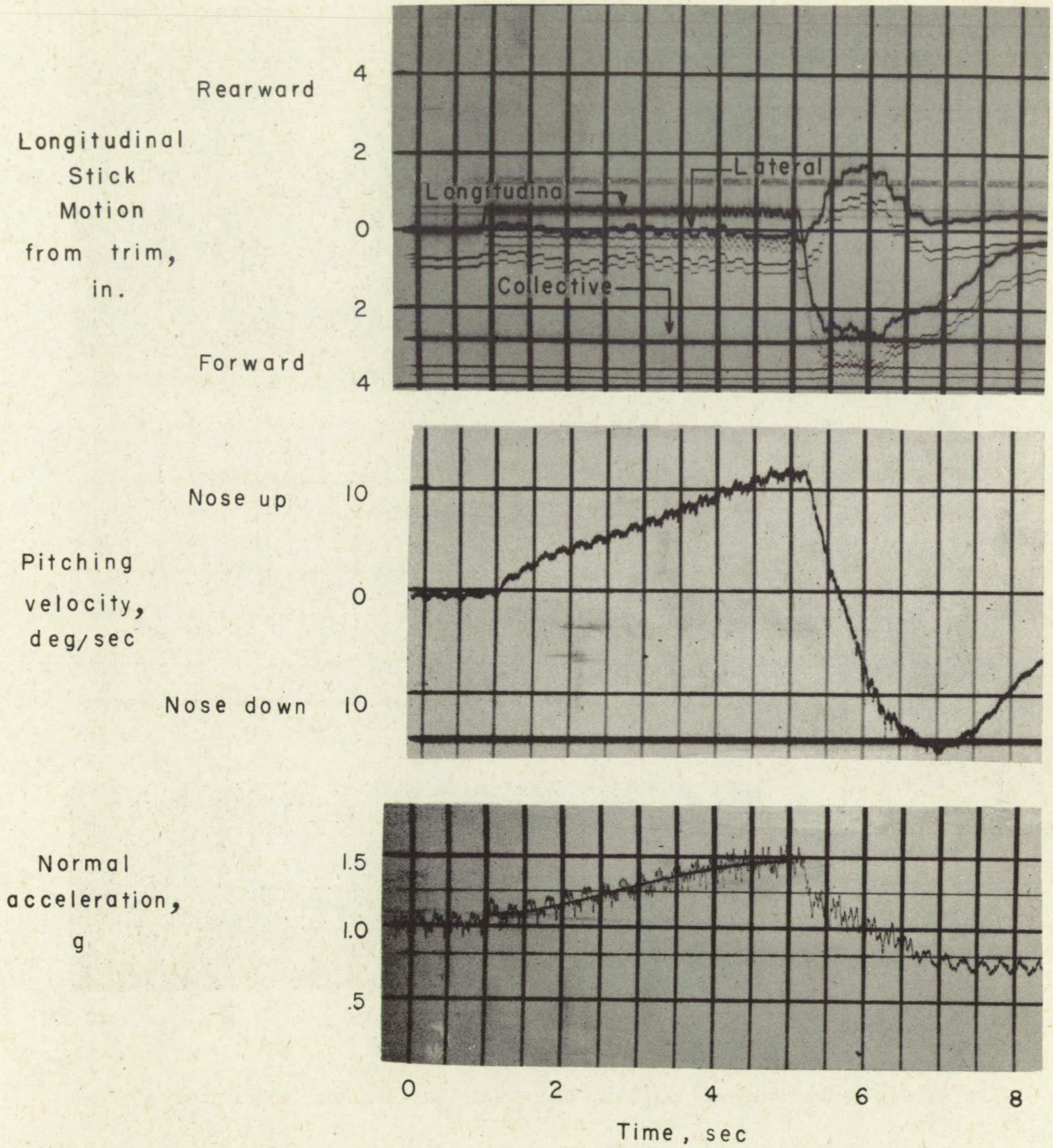

Figure 3.- Time history of pull-up maneuver for tandem helicopter at flight condition B.

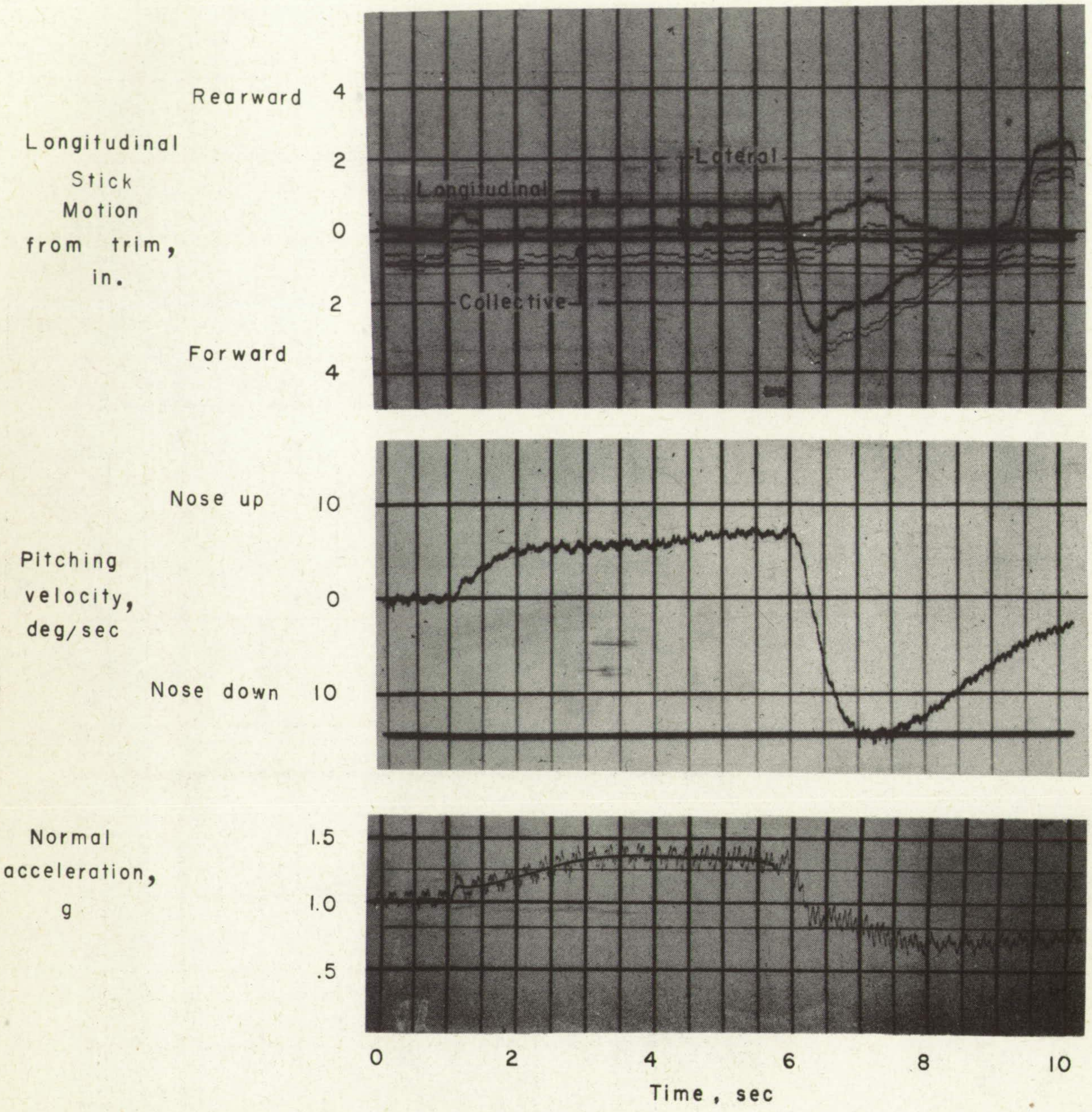

Figure 4.- Time history of pull-up maneuver for tandem helicopter at flight condition C.

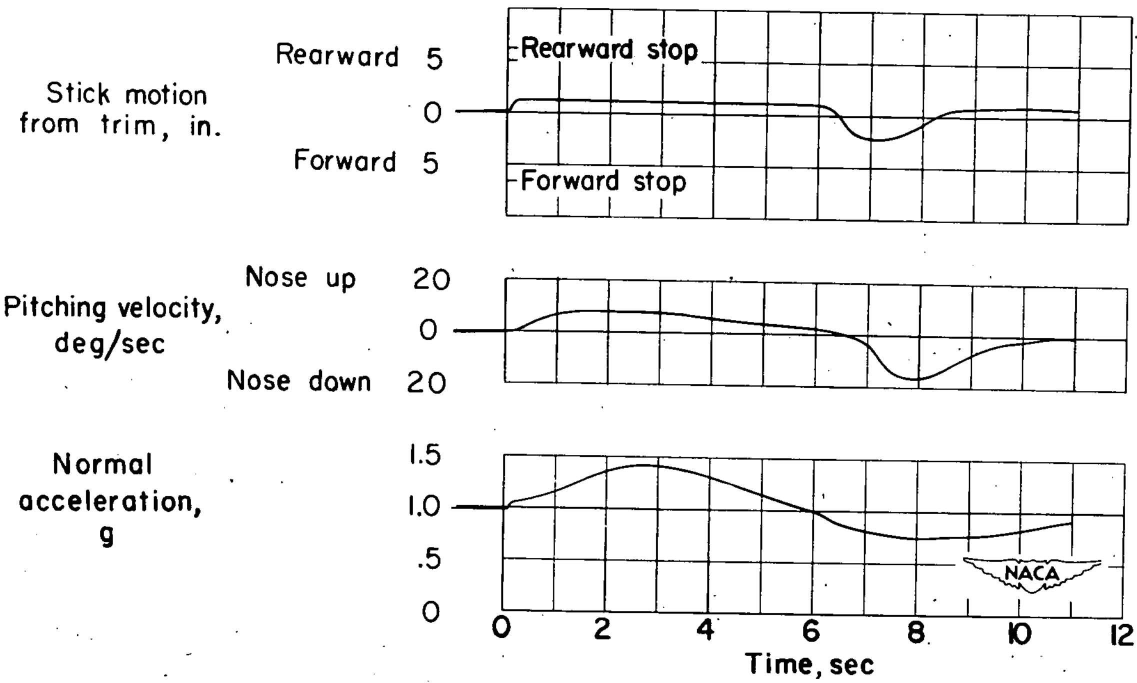

Figure 5.- Time history of pull-up maneuver for a single-rotor helicopter of reference 2.